Effect of dipolar interactions for domain wall dynamics in magnetic thin films

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***Abstract*—We study the effect of long range dipolar forces on the dynamics and morphology of domain walls in magnetic thin films by numerical simulations of the spin-1 random field Ising model. By studying the size distribution of avalanches of domain wall motion arising as a response to quasistatic external driving, we observe a cross-over from the case dominated by short range interactions to another universality class where the long range dipolar forces become important. This crossover is accompanied with a change of the domain wall morphology from a rough wall to walls with zigzag structure.**

I. Introduction

THE study of ferromagnetic thin films is an open field of current interest both from a technological and fundamental point of view. On the one hand ferromagnetic thin films are of interest because of their applications in a diverse range of fields, such as magnetic recording technology and spintronics [1], while on the other they are of interest because there remain a number of unanswered questions regarding their hysteretic properties, such as the Barkhausen effect.

The Barkhausen effect is the name given to the noise in the magnetic output generated in a ferromagnetic material when the magnetizing field applied to it is changed [2]. The origin of this noise is due to the jerky fashion in which magnetic domain walls move in response to a slowly varying externally applied magnetic field. The motion is irregular because the domain wall can become pinned, at various points, by impurities in the material. By increasing the strength of the external field the domain wall can become locally depinned and moves forward, only to become trapped once again by more impurities further ahead [3].

The statistical properties of the Barkhausen effect are quantitatively understood in bulk three dimensional materials by the theory of domain wall depinning [4], [5]. The experiments can be classified into universality classes depending on the strength of dipolar interaction [6]. On the other hand, our understanding of Barkhausen noise in ferromagnetic thin films is incomplete. Recent experiments show that the morphology of the domain wall depends strongly on temperature [7]. At temperatures well below the Curie temperature, with high saturation magnetization, the domain wall is observed to have a zigzag structure to minimise the the dipolar interaction energy. However, upon approaching the Curie temperature the morphology of the domain wall is dominated by line tension and is observed to form a rough interface free of large zigzags. These two regimes correspond to different Barkhausen noise universality classes and the exponents exhibit a crossover as a function of temperature.

Here we demonstrate that this crossover can be understood by considering the effect of the long range dipolar forces on the morphology and dynamics of a magnetic domain wall in a thin ferromagnetic material. We consider a head-on domain wall consisting of two domains of opposite in plane magnetisation, due to large anisotropy along the easy axis. This situation we model as a three state spin-1 Ising Hamiltonian [8], whereby the interaction between neighbouring spins is ferromagnetic and is in competition with a long range (antiferromagnetic) dipole-dipole interaction. In addition the Hamiltonian also includes a random quenched field (which represents the effect of pinning sites) and an extra term which models the effect of an external magnetic field. By increasing the magnitude of the external field we can drive the domain wall forward over the pinning sites and collect statistics for the avalanche size distributions. Doing this for a range of values of the saturation magnetisation we confirm that behaviour of the Barkhausen noise can be described by two separate universality classes, depending on the value of the saturation magnetization. The paper is organized as follows: In the next Section we present the simulation model, followed by an overview of the numerical results in Section III. Section IV finishes the paper with conclusions.

II. Model

We simulate the dipolar spin 1 random field Ising model (RFIM) in a 2D triangular lattice with in plane magnetization. A similar model was studied in Ref. [8] with out of plane magnetization. The Hamiltonian is given by

$$\begin{aligned}\mathcal{H} &= -J\sum_{\langle ij\rangle} s_i s_j - \sum_i [(H+h_i)s_i - \frac{1}{2}As_i^2] + \\ &\quad +D\sum_{ij} s_i s_j \frac{1-3\cos^2\theta_{ij}}{r_{ij}^3},\end{aligned} \tag{1}$$

where the first term describes the exchange interactions between nearest neighbour spins with a strength J, the second term takes into account the contributions of the applied external field H and the parameter A controls the relevance

of the $s_i = 0$ state, respectively. The third term includes the dipolar interactions between two spins s_i and s_j at a distance r_{ij} , with a strength $D = \mu_0 M_s^2/2\pi$, where M_s is the saturation magnetization. In the simulations, we also add a fictitious demagnetizing energy $E = 1/2kM^2$, with k the demagnetizing factor and $M = M_s \sum_i s_i/N$ the total magnetization of the system. This final term has been introduced only for computational convenience, since dipolar interactions are accounted for by the third term, and allows the domain wall to be kept around the coercive field. In experiments this situation is realised by recording magnetization dynamics slightly below the coercive field H_c and then letting the domain wall move by thermal activation. This case would be slower to simulate with our model, but avalanche statistics is expected to be same in the limit of small k. Finally, we note that disorder is modeled by in the system by a quenched random field h_i extracted from a Gaussian distribution with variance R.

To study the avalanche dynamics and the morphology of the domain walls, we simulate the model on a two dimensional lattice of size $L \times 2L$, with $L = 256$, in $T = 0$ with extremal dynamics (meaning that after each avalanche the external field is ramped up to the point where just a single spin is about to flip, the spin is then allowed to flip and this initiates the next avalanche). We consider weak disorder, setting $R/J = 1/2$.

In this limit, a spin-1 model is convenient in describing the domain wall dynamics since the intermediate $s_i = 0$ state causes the domain walls to have a finite width so that spurious lattice effects are less pronounced than in systems where an abrupt transition between neighboring domains takes place. Such lattice effects, which are a problem in the spin $\frac{1}{2}$ case, include faceting a case in which the length of a boundary between two points has a different value depending on its orientation with respect to the crystallographic axis [9]. Lattice anisotropy is also reduced using a triangular lattice, instead of the more conventional square lattice. Finally, the parameter A is chosen so that problem of faceting, as described above, is minimized - which according to our simulations occurs for $A \simeq 2J$. The simulations are started from a state with all spins $s_i = -1$ except at the bottom layer of the system where a boundary condition $s_i = 1$ is imposed. This creates an initially flat head-to-head domain wall in the system. The external field value is then increased from zero until the first spin at the domain wall becomes unstable, i.e. the local field H_i of the spin s_i given by

$$\begin{aligned} H_i &= J \sum_{\langle ij \rangle} s_j + H + h_i - A s_i - \\ & -D \sum_{ij} s_j \frac{1 - 3\cos^2\theta_{ij}}{r_{ij}^3} - kM \end{aligned} \qquad (2)$$

changes sign (note here we have explicitly included the fictitious demagnetizing term). This spin is then flipped from $s_i = -1$ to $s_i = 0$, or from $s_i = 0$ to $s_i = 1$. Due to the interactions between different spins (both through the local exchange interactions and the long range dipolar fields), this initial spin flip can cause other spins to flip as well, leading to a cascade of activity or an avalanche. The external field is kept constant during such an avalanche. The avalanche size

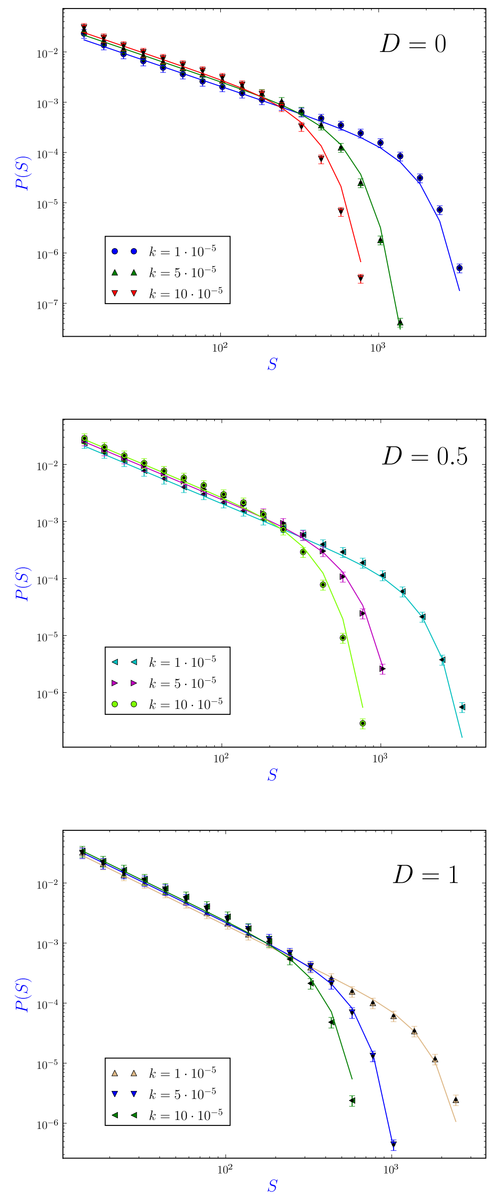

Fig. 1. The avalanche size distributions for different strengths of the dipolar interaction, along with fits of the form of Eq. (3). The top panel shows the case with $D = 0$ (with $\tau = 1.07 \pm 0.03$, $\sigma_k = 0.64 \pm 0.02$ and $n = 3.1 \pm 0.4$), followed by $D = 0.5$ (with $\tau = 1.17 \pm 0.03$, $\sigma_k = 0.64 \pm 0.02$ and $n = 2.6 \pm 0.3$) and $D = 1$ (with $\tau = 1.35 \pm 0.03$, $\sigma_k = 0.64 \pm 0.02$ and $n = 2.5 \pm 0.2$).

S is defined as the total number of spins flipped during an avalanche. All the spin flips are taken to proceed via the intermediate $s_i = 0$ state, and only spins at the domain wall are flipped, preventing domain nucleation in front of the interface. Each time the activity stops, the magnitude of the external field H is again increased by an amount which causes one of the spins on the lattice to become unstable, and a new avalanche is initiated. This procedure is repeated until the domain wall has moved from one end of the system to the other. Notice that the inclusion of the term describing the effects of the demagnetizing fields keeps the domain wall close to the critical point of the underlying depinning transition as the external

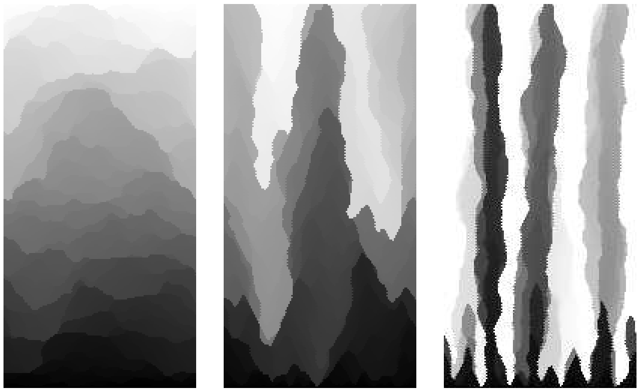

Fig. 2. Examples of domain evolution patterns for $D = 0$ (left), $D = 0.5$ (middle) and $D = 1.0$ (right). The different grayscale colors correspond to time (flowing from black to white) such that the area of each avalanche has its own grayscale. Notice the change in the domain wall morphology as the strength of the dipolar forces is increased.

field H is ramped up.

III. Numerical results

Simulations are performed with $R = 1$, $J = 2$, $A = 4$, three different values of the dipolar interaction strength ($D = 0, 0.5$ and 1) and of the demagnetizing factor k. Notice that k and D should in principle be related. Here, we vary them independently for computational purposes, since k alone is expected to determine the avalanche cut-off [6]. The avalanche size distributions are fitted by a power law with a cut-off,

$$P(S) = CS^{-\tau} \exp\left[-\left(\frac{S}{S_0}\right)^n\right], \quad (3)$$

where C is a normalization constant, τ is the exponent characterizing the universality class of the avalanche dynamics, $S_0 = k^{-\sigma_k}$ gives the dependence of the cut-off scale S_0 on the demagnetizing factor k [6], and n is a fitting parameter related to the shape of the cut-off function. Fig. 1 shows the distributions for the three values of $D = 0, 0.5$ and 1 and three values of k. For each value of D, we perform a simultaneous least-square minimization on the three curves corresponding to the three values of k. The best least-squares fits to the data give $\tau = 1.07 \pm 0.03$ for $D = 0$, $\tau = 1.17 \pm 0.03$ for $D = 0.5$, and $\tau = 1.35 \pm 0.03$ for $D = 1$. The other parameter values are $\sigma_k = 0.64 \pm 0.02$ for all three cases, and $n = 3.1 \pm 0.4$, $n = 2.6 \pm 0.3$ and $n = 2.5 \pm 0.2$ for $D = 0$, 0.5 and 1, respectively. The values of the avalanche size exponent τ are in excellent agreement with the results reported in Ref. [7] for MnAs thin films, reporting a crossover between $\tau = 1.33$ and $\tau \simeq 1$ as the saturation magnetization M_s was decreasing due to the temperature increase. In addition, the exponent for the case without dipolar interactions is close to the theoretically expected value of $\tau \simeq 1$ for the $1 + 1$ dimensional interface depinning of the short range interaction universality class [10], [11]. When the strength of the dipolar interactions is increased, we observe a crossover to a different exponent value, close to the value reported for a lattice model for zigzag domain walls [12].

By inspecting the domain wall morphology in Fig. 2 we observe that this change in the exponent value is accompanied with a change in the domain wall structure: For low D, the domain walls are almost flat, with some roughness due to the interaction with the random field disorder. For larger values of D, a characteristic zigzag or sawtooth pattern develops, as a result of the interface trying to minimize the magnetostatic energy due to the magnetic charges at the interface. This feature is again in excellent agreement with the experiment [7].

IV. Conclusions

Our simulations demonstrate a striking change in the morphology of a head-on domain wall as the saturation magnetisation is increased. It is clear that this change in the morphology is responsible for the cross-over between the two universality classes, as evidenced by the change in value of the avalanche size exponent τ. This difference helps explain, in part, the variation in the experimentally measured scaling exponents.

However, despite this success we believe that the present model is subject to limitations due to the underlying lattice symmetry of the model. It is well known that lattice effects can have an unwanted influence on the dynamics/morphology of a system and this can only be overcome by simulating prohibitively large systems. In order to obtain a faithful estimation of the avalanche size exponents it is necessary instead to consider an ’off-lattice’ model. In such a model the object of interest is the domain wall itself, which can be described as a series of vertices connected by straight edges. The various interactions between spins can be interpreted as forces acting on the domain wall, while the position of the vertices describing the domain wall become the degrees of freedom of the system. Such a model is currently under investigation by the present authors.

Acknowledgment

LL wishes to thank Academy of Finland for financial support.

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